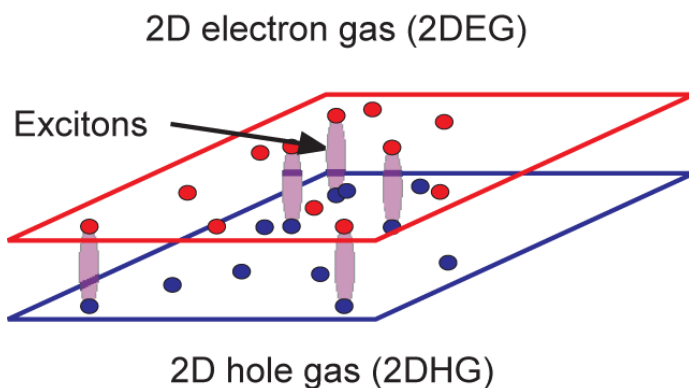


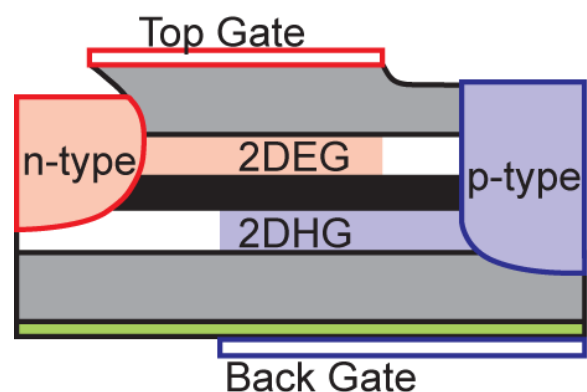
# Materials Science and Technology

## Nanoelectronics

# Converting Fermions to Bosons in Electron-Hole Bilayers



**Figure 1:** Excitons are present as electron and hole pairs that form across opposite layers.



**Figure 2:** Schematic cross section of the undoped electron-hole bilayer sample: the conducting areas of the 2DEG (2DHG) are in red (blue), the  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  ( $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ ) barriers are in grey (black), and a insulating SiN layer is shown in green.

*Fundamental low  
temperature physics  
is made possible by  
Sandia's expertise in  
heterostructure growth  
and device fabrication*

For more information:

**Technical Contact:**  
Mike Lilly  
505-844-4395  
mplilly@sandia.gov

**Science Matters Contact:**  
Alan Burns  
505-844-9642  
aburns@sandia.gov

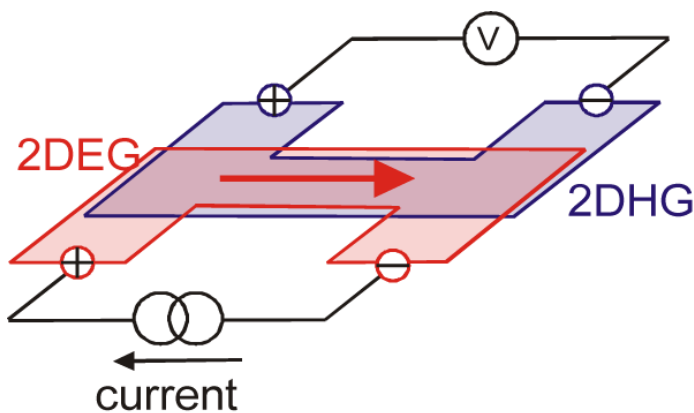
In quantum mechanics, a particle is identified by a wavefunction that contains spatial and spin components. Collections of identical particles obey fundamental statistical rules that are determined by their spin state. Particles with half-integer spins (e.g., electrons) are fermions, and particles with integer spins (e.g., photons) are bosons. Electronic, thermal and other properties are strongly impacted by these statistics. For example, fermions must obey the Pauli exclusion principle that doesn't allow any two fermions to occupy the same quantum state. Bosons, on the other hand, can occupy exactly the same state, and at very low temperatures they collapse into a single quantum state called a Bose-Einstein condensate (BEC). Interestingly, when two fermions couple together, they look like a boson. One case where this occurs is when an electron and hole pair up in a semiconductor and form an exciton (Figure 1). Experiments at Sandia are trying to identify the transition from electrons and holes acting like fermions to the exciton acting like a boson.

Creating the appropriate electron and hole systems is extremely challenging. For BEC to occur, the electrons and holes need to be confined to two dimensions and be spatially separated into a bilayer. Sandia's expertise in growing high quality GaAs heterostructures and performing advanced semiconductor processing is critical to the success of this project. A cross section of a structure is shown in Figure 2. The primary measurement in these systems is a four-wire resistance measurement at very low temperature. For the typical resistance measurement in electronic materials, current is driven between two contacts and the voltage is measured between two different contacts. In the Sandia bilayers, current is driven in the electron layer and voltage is measured in a *different* layer, as shown in Figure 3. This configuration is called Coulomb drag, and the resistivity has units of  $\Omega/\square$  where  $\square$  represents the length divided by the width. For weakly coupled electrons and holes, the Coulomb drag measurement is dominated by electron-hole scattering, and vanishes as the temperature is

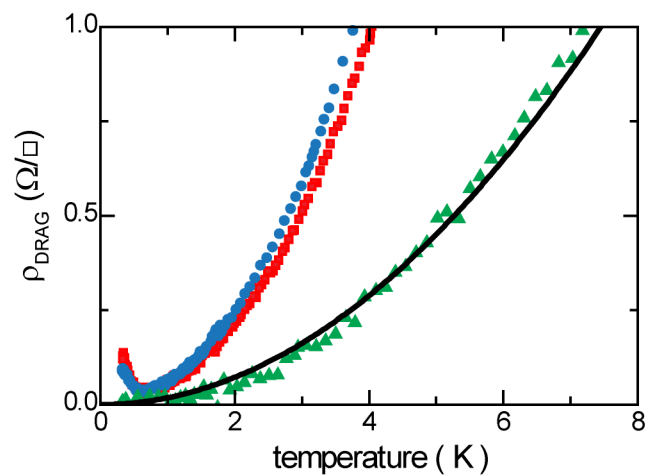
reduced. When excitons form, the electronic coupling between the layers is much larger, and the drag signal is expected to increase. In fact, the drag is predicted to diverge when Bose-Einstein condensation occurs.

In Figure 4, the drag resistance ( $\rho_{\text{DRAG}}$ ) for three devices is shown for electron (n) and hole (p) densities  $n = p = 8 \times 10^{10} \text{ cm}^{-2}$ . Each has a different barrier thickness between the electron and hole conducting layers (see Figure 2). The drag for the wider barrier sample (green, 30 nm barrier) is quadratic with temperature. The two narrow barrier devices (blue and red, 20 nm barrier) are initially quadratic, but below the temperature of 0.5 K a significant deviation develops. Here the drag reaches a minimum, and for lower

temperatures there is a pronounced *upturn* of  $\rho_{\text{DRAG}}$  where it *increases with decreasing temperature*. The increase in drag indicates the development of a strong coupling between the electron and hole layers. While there is not enough evidence to conclude that Bose-Einstein condensation has occurred, we believe the increase in drag is due to the formation of excitons in the system. Thus, the next step is to fabricate and study electron-hole bilayer structures with thinner barriers and at lower temperatures. Another step is to broaden the transport techniques to include counter-flow where currents are flowing in opposite directions in each layer. The counter-flow measurement is expected to be sensitive to the superfluid component of an exciton condensate.



**Figure 3:** Coulomb drag measurement where current flows in electron (2DEG) layer while voltage is measured in the hole (2DHG) layer.



**Figure 4:** Drag resistivity at  $n = p = 8 \times 10^{10} \text{ cm}^{-2}$  for three devices. Sample A, 30 nm barrier, (green triangles), Sample B, 20 nm barrier, (red squares), and Sample C, 20 nm barrier, (blue circles). The line is a  $T^2$  best fit for the electron hole bilayer with a 30 nm barrier.